

# Spin Filtering of Stored (Anti)Protons: from FILTEX to COSY to AD to FAIR <sup>1</sup>

Nikolai Nikolaev and Fyodor Pavlov

*Institut für Kernphysik, Forschungszentrum Jülich, 52428 Jülich, Germany*

**Abstract.** We review the theory of spin filtering of stored (anti)protons by multiple passage through the polarized internal target (PIT). Implications for the antiproton polarization buildup in the proposed PAX experiment at FAIR GSI are discussed.

**Keywords:** Spin filtering

**PACS:** 24.70.+s, 29.27.Hj

An ambitious physics program with polarized antiproton–polarized proton collider has been proposed recently by the PAX Collaboration [1] for FAIR at GSI in Darmstadt, Germany [2]. Such a collider would give an unique access to the last leading–twist missing piece of the QCD partonic structure of the nucleon — the transversity — which can only be investigated via double–polarized  $\bar{p}p$  Drell–Yan production and without which the spin tomography of the proton would be ever incomplete. At the core of the PAX proposal is spin filtering of stored antiprotons by multiple passage through a Polarized Internal hydrogen gas Target (PIT) [1, 3] — a technique tested by the FILTEX experiment at 23 MeV proton TSR-ring in Heidelberg [4]. In its extension to antiprotons there remain open issues, though.

In his theory of the FILTEX result, H. O. Meyer (i) observed that stored particles which scatter elastically in PIT at angles within a storage ring acceptance angle  $\theta_{\text{acc}}$  are retained in the beam and their polarization complements the polarization by transmission and (ii) argued that the QED polarization transfer from polarized target electrons to scattered protons [5] is crucial for the quantitative understanding of the FILTEX result [6]. This prompted an idea to base the antiproton polarizer of the PAX on spin filtering by polarized electrons in PIT [3].

After the PAX proposal, the interplay of the transmission and Scattering Within the Ring Acceptance Angle (SWRAA) mechanisms, and the feasibility of filtering on electrons, became a major issue. Yu. Shatunov <sup>2</sup> was perhaps the first to question the filtering by electrons. Eventually two groups of theorists — at the Budker Institute [7] and IKP, Jülich [8] — came to a conclusion on the self-cancellation of the polarized electron contribution to the spin filtering of (anti)protons. Here we present a brief review of this finding and its implications for the PAX program.

There is an important hierarchy of scattering angles  $\theta$  in the proton-atom scattering. First, the Coulomb fields of the proton and atomic electron screen each other for scattering angles  $\theta < \theta_{\text{min}} = \alpha_{\text{em}} m_e / \sqrt{2m_p T_p} \approx 2 \cdot 10^{-2}$  mrad ( $T_p = 23$  MeV). Second, light electrons do not deflect protons,  $\theta \leq \theta_e = m_e / m_p \approx 5 \cdot 10^{-1}$  mrad. Third comes the

<sup>1</sup> Presented at the 17th Intl. Spin Physics Symposium, SPIN2006, Kyoto, Japan, October 2-7, 2006

<sup>2</sup> Yu. Shatunov, private communication

Colomb-Nuclear Interference (CNI) angle  $\theta_{CNI} \approx \sqrt{2\pi\alpha_{em}/m_p T_p \sigma_{tot,nuc}^{pp}} \approx 100\text{mrad}$ . Fourth for the TSR  $\theta_{acc} = 4.4 \text{ mrad}$ , and  $\theta_{min} \ll \theta_e \ll \theta_{acc} \ll \theta_{CNI}$ . For important angles  $\theta > \theta_{min}$  the proton-atom interaction is dominated by quasielastic (QE) scattering,  $p + atom \rightarrow p'_{scatt} + e_{spect} + p_{recoil}, p'_{scatt} + p_{spect} + e_{recoil}$  ( $\mathbf{q}$  is the momentum transfer,  $\hat{\rho}$  — the beam spin-density matrix):

$$\frac{d\hat{\sigma}_{QE}}{d^2\mathbf{q}} = \frac{1}{(4\pi)^2} \hat{\mathcal{F}}(\mathbf{q}) \hat{\rho} \hat{\mathcal{F}}^\dagger(\mathbf{q}) = \frac{1}{(4\pi)^2} \hat{\mathcal{F}}_e(\mathbf{q}) \hat{\rho} \hat{\mathcal{F}}_e^\dagger(\mathbf{q}) + \frac{1}{(4\pi)^2} \hat{\mathcal{F}}_p(\mathbf{q}) \hat{\rho} \hat{\mathcal{F}}_p^\dagger(\mathbf{q})$$

In our normalization the forward scattering amplitude  $\hat{F}(0) = \hat{R}(0) + i\hat{\sigma}_{tot}$ . For spin- $\frac{1}{2}$  beam and target  $\hat{\sigma}_{tot} = \sigma_0 + \sigma_1(\sigma \cdot Q) + \sigma_2(\sigma \cdot \mathbf{k})(Q \cdot \mathbf{k})$ , where  $\mathbf{k}$  is the beam axis,  $Q$  and  $P$  are the target and beam polarizations.

Let  $N$  be the volume density of atoms in PIT and  $z$  the integrated thickness of the PIT for a circulating particle. The spin-momentum density matrix of the beam,  $\hat{\rho}(\mathbf{p}) = \frac{1}{2}[I_0(\mathbf{p}) + \sigma\mathbf{s}(\mathbf{p})]$ , satisfies the evolution equation

$$\begin{aligned} \frac{d\hat{\rho}}{dz} = & \underbrace{i\frac{1}{2}N(\hat{R}\hat{\rho}(\mathbf{p}) - \hat{\rho}(\mathbf{p})\hat{R})}_{\text{Precession in transmission}} - \underbrace{\frac{1}{2}N(\hat{\sigma}_{tot}\hat{\rho}(\mathbf{p}) + \hat{\rho}(\mathbf{p})\hat{\sigma}_{tot})}_{\text{Filtering by transmission}} \\ & + \underbrace{N \int^{\Omega_{acc}} \frac{d^2\mathbf{q}}{(4\pi)^2} \hat{\mathcal{F}}(\mathbf{q}) \hat{\rho}(\mathbf{p} - \mathbf{q}) \hat{\mathcal{F}}^\dagger(\mathbf{q})}_{\text{Feedback from SWRAA}} \end{aligned} \quad (1)$$

The stable polarization are either normal to ring plane (the case in the FILTEX experiment) or longitudinal if a ring is furnished with the Siberian Snakes. The precession effects are very important in the polarized neutron optics but average out in our case. Upon neglecting the precession terms  $\propto \hat{R}$ , Eq. (1) boils down to the kinetic equation for spin population numbers. For real storage rings Eq. (1) further simplifies because the angular divergence of the beam at PIT is much smaller than  $\theta_{acc}$ . The FILTEX PIT used the hyperfine state with parallel proton and electron polarizations.

The real issue is a pattern of a (partial) cancellation of transmission and SWRAA effects in Eq. (1). Without spin-flip, the polarization buildup follows  $P(z) = -\tanh(Q\sigma_P Nz)$  where  $\sigma_P = \sigma_1$ . Because only those particles which scatter in PIT at angles  $\theta > \theta_{acc}$  are removed from the stored beam, Meyer argued that the transmission be evaluated taking  $\hat{\sigma}_{tot} = \hat{\sigma}_{tot}(\theta_{acc} < \theta)$ . For all-angle nuclear interaction without CNI, the SAID phase shifts give  $\sigma_{1,nuclear} = 122 \text{ mb}$ , upon the correction for CNI Meyer found  $\sigma_1(CNI; \theta > \theta_{acc}) = 83 \text{ mb}$  vs. the published FILTEX result  $\sigma_P(FILTEX, 1993) = 63 \pm 3 \text{ (stat.) mb}$ . Next Meyer includes the polarization from SWRAA. In view of  $\theta_e \ll \theta_{acc}$ , the scattering off electrons is entirely SWRAA and contributes  $\delta\sigma_1^{ep}(\theta < \theta_{acc}) = -70\text{mb}$ . SWRAA off protons contributes  $\delta\sigma_1^{pp}(\theta < \theta_{acc}) = +52 \text{ mb}$ . Meyer's net result for the polarization cross section [6],

$$\sigma_P = \sigma_1(CNI; \theta > \theta_{acc}) + \delta\sigma_1^{pp} + \delta\sigma_1^{ep} = 135 \text{ mb} + \delta\sigma_1^{ep} = 65 \text{ mb}, \quad (2)$$

is in perfect agreement with the published FILTEX result. A subsequent reanalysis of the target density and polarization gave  $\sigma_P(FILTEX, 2004) = 72.5 \pm 5.8 \text{ (stat. + sys.)}$  (F.Rathmann, see [1]).

The Budker and Jülich groups argue that  $\hat{\sigma}_{tot}$  in the transmission term must rather include a scattering on atoms at all angles  $\theta > \theta_{min}$ :  $\hat{\sigma}_{tot} = \hat{\sigma}_{tot}(\theta_{min} > \theta) = \hat{\sigma}_{tot}(\theta_{min} < \theta < \theta_{acc}) + \hat{\sigma}_{tot}(\theta_{acc} < \theta)$ . Then one would readily find that the beam polarization-independent SWRAA cancels exactly the corresponding transmission effects from  $\hat{\sigma}_{tot}(\theta_{min} < \theta < \theta_{acc})$ . For a polarized beam there is a mismatch between the spin-filtering component in  $\hat{\sigma}_{tot}(\theta_{min} < \theta < \theta_{acc})$  and the polarization feedback from SWRAA. This mismatch is entirely due the spin-flip elastic proton-atom scattering at angles  $\theta < \theta_{acc}$ . The generic solution for the polarization buildup reads

$$P(z) = -\frac{Q(\sigma_1 + \Delta\sigma_1) \tanh(Q\sigma_3 Nz)}{Q\sigma_3 + 0.5\Delta\sigma_0 \tanh(Q\sigma_3 Nz)}, \quad (3)$$

where  $\Delta\sigma_{0,1}$  are the proton spin-flip (SF) cross sections for an unpolarized and polarized target, respectively,  $|\Delta\sigma_1| \leq |\Delta\sigma_0|$ , and  $Q\sigma_3 = \sqrt{Q^2\sigma_1(\sigma_1 + \Delta\sigma_1) + \Delta\sigma_0^2/4}$ . The formulas for  $\Delta\sigma_{0,1}$  in terms of the two-spin observables are found in [7, 8]. In contrast to the Meyer approach, in the Budker-Jülich analysis the electron-to-proton polarization transfer is entirely canceled by the electron contribution to the transmission filtering. For nuclear SF scattering at  $\theta \leq \theta_{acc} \ll \theta_{CNI}$  CNI is arguable negligible and a crude estimate is  $\Delta\sigma_0 \lesssim \sigma_{tot}\theta_{acc}^2 \lesssim 10^{-4}\sigma_{tot}$ . Within the Budker-Jülich approach, the small-time polarization buildup is controlled by (SAID-SP05 database)

$$\sigma_P \approx -(\sigma_1(CNI; \theta > \theta_{acc}) + \Delta\sigma_1) = 85.6 \text{ mb}. \quad (4)$$

The case of the pure electron target deserves a special consideration. Here  $\sigma_0(\theta > \theta_{acc}) = 0$ ,  $\sigma_1(\theta > \theta_{acc}) = 0$ ,  $Q\sigma_3 = \Delta\sigma_0$ , the beam is not attenuated and the polarization buildup follows

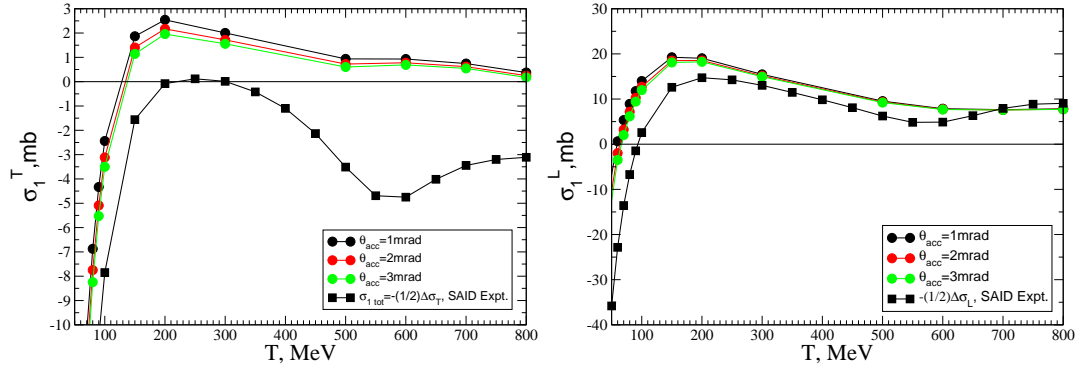
$$P(z) = P(0) \exp(-N\Delta\sigma_0 z) + Q \frac{\Delta\sigma_1}{\Delta\sigma_0} \left\{ 1 - \exp(-N\Delta\sigma_0 z) \right\}. \quad (5)$$

Spin filtering by electron coolers was discussed in the PAX TP with the conclusion that the attainable target densities are too low [1]. More recently, Th. Walcher et al. <sup>3</sup> argued that if the SF on electrons is comparable to the electron-to-proton spin transfer, then filtering in a pure electron target can be enhanced considerably by a judicious choice of the non-relativistic relative velocity of the comoving electron and proton beams. At the moment, based only on the FILTEX result, one can not discriminate between the Meyer and Budker-Jülich treatments of the electron contribution to filtering; as it is a common practice with conflicting theories, the issue must be clarified experimentally.

First, the filtering by SF has never been tested experimentally. If the polarized electron target polarizes the initially unpolarized stored beam, the unpolarized electron target depolarizes the stored proton beam, see Eq. 5. The required density of electrons is provided by the  $^4\text{He}$  internal target, which has an advantage of the spin-0 nucleus. Consequently, a useful upper bound on depolarization by electrons, i.e.,  $\Delta\sigma_0$  and  $|\Delta\sigma_1| \leq$

---

<sup>3</sup> Th. Walcher, private communication



**FIGURE 1.** Predictions for spin filtering of protons by nuclear interaction in polarized hydrogen PIT for transverse (T) and longitudinal (L) polarizations. The curves marked by back squares are for pure nuclear  $pp$  interaction, the three curves for different range acceptance angle are predictions with allowance for CNI.

$|\Delta\sigma_0|$  can be deduced. Such an experiment, the idea of which grew up from discussions with H.O. Meyer, is being planned at COSY [9]. Second, filtering on electrons and on protons have a very distinct energy dependence. In Fig. 1 we show the predictions from the Budker-Jülich approach for the nuclear spin filtering cross section which can be tested at COSY. The confirmation of this energy dependence would be a convincing proof that spin filtering is dominated by nuclear interaction of a negligible filtering on electrons.

We come to a summary. FILTEX experiment is an important proof of the principle of spin filtering. The Meyer and Budker-Jülich approaches disagree in the treatment of SWRAA and significance of the electron contribution to spin filtering. If the electrons do not contribute (Budker-Jülich), then filtering of antiprotons would depend on spin-dependence of  $\bar{p}p, \bar{p}D$  interactions. The existing models of  $\bar{N}N$  interactions are encouraging but not reliable because of a lack of double-spin observables to fix the model parameters. The solution for PAX is to optimize the filtering energy with antiprotons available at existing facilities (CERN AD) [9]. The experimental constraints on the electron contribution to filtering can be obtained from proton depolarization and energy-dependence of filtering of protons at COSY.

## REFERENCES

1. PAX Technical Proposal for the HESR at FAIR, Jülich (2004), Spokespersons: P. Lenisa and F. Rathmann. e-Print Archive: hep-ex/0505054. For the update see <http://www.fz-juelich.de/ikp/pax/>
2. H. Ströher, these Proceedings.
3. F. Rathmann et al., Phys. Rev. Lett. **94**, 014801 (2005).
4. F. Rathmann et al., Phys. Rev. Lett. **71**, 1379 (1993).
5. C.J. Horowitz and H.O. Meyer, Phys. Rev. Lett. **72**, 3981 (1994).
6. H.O. Meyer, Phys. Rev. **E50**, 1485 (1994).
7. A. I. Milstein and V. M. Strakhovenko, Phys. Rev. E **72**, 066503 (2005)
8. N. N. Nikolaev and F. F. Pavlov, e-Print Archive: hep-ph/0512051, hep-ph/0601184.
9. F. Rathmann, these Proceedings.